Layered Organization in the Coastal Ocean:
4-D Assessment of Thin Layer Structure, Dynamics and Impacts

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GOAL

Our long-term goal is to understand (1) the properties of densely concentrated, thin layers of planktonic biota that can occur in coastal ocean environments, (2) the interacting physical, chemical, biological and optical processes responsible for establishment, maintenance and breakdown of layers, (3) the impact of thin layers on the dynamics of plankton populations and the performance of optical sensors, and (4) how the above vary between coastal systems that differ in physical size, exposure to physical forcing, and susceptibility to episodic events.

OBJECTIVES

Our objectives for this LOCO project are (1) to understand the physical, biological, optical, chemical and acoustical properties of vertically thin horizontal layers of biota and biogenic particles in coastal oceans, and the processes responsible for the formation, maintenance and dissipation of layers; (2) to understand the spatial coherence and spatial properties of thin layers in the coastal ocean (especially in terms of optical properties), as well as the temporal durability of layers, where they occur; and (3) to use the information gleaned in the first two objectives along with data from our studies in other coastal systems to test and refine our models of thin layer dynamics (Donaghay and Osborn, 1997) and thus continue to develop the ability to predict layer formation and presence in the coastal ocean. Our primary objectives during the past 12 months of this grant have been to (1) process the raw data from the 2005 and 2006 LOCO field experiments into master data files that include all measured and derived parameters, and (2) begin to use the data to address our overall scientific objectives. Our secondary objective was to continue to publish the results of our previous work on thin layers.

APPROACH

Our approach during the 2005 and 2006 LOCO process study combined time series data from an array of our Ocean Response Coastal Analysis System (ORCAS) (Donaghay, 2004; Babin, et al, 2005)

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autonomous bottom-up profilers with spatial data collected over a broader area using our ship-deployed, high-resolution profiler. These efforts were done in close collaboration with LOCO projects led by Holliday, Hanson, Rines, Goodman, and McManus. Our efforts are discussed below along with collaborations in collecting and analyzing the data.

The first major component of our effort involved using an array of autonomous profilers to simultaneously collected temporal data on the spatial variations in vertical fine-scale physical, chemical, optical, and acoustical structure. We deployed two of our ORCAS bottom-up profilers 100 m apart in the cluster located at K1 and a third profiler at station K2 located 1 km further offshore along the cross-shelf K line. This design allowed us to sample simultaneously at two different spatial scales. The profilers collected centimeter-resolution profiles at least once an hour of temperature, salinity, depth, oxygen, spectral absorption, spectral attenuation, spectral scattering, backscatter at 532 nm, chlorophyll a fluorescence, and CDOM fluorescence. Our ORCAS profilers at K1 South and K2 had a Nortek ADV (Acoustic Doppler Velocity meter) for simultaneously measuring centimeter- scale currents and turbulence. Our ORCAS profiler at K1 North had the same suite of sensors as the other profilers except that had additional sensors for nutrients (a SubChem Systems autonomous nutrient analyzer provided by Hanson) and light (Satlantic OCR-4 downwelling light sensor). In addition, the multi-spectral WET Labs ac-9 was replaced on this profiler with a WET Labs ac-s hyper-spectral absorption and attenuation and meter. Other time series sensors at each of these locations included a TAPS multi-frequency acoustics zooplankton profiler deployed by Holliday, an ADCP for measuring currents and current shear once a minute with 25-50 cm resolution (deployed by Holliday or McManus) and a thermister string for measuring internal waves (deployed by Holliday or McManus). Data from our array of profilers was radioed to shore at the end of each profile. Near-real time preliminary analysis of this data was used to quantify temporal changes in physical, chemical and optical structure and look for the occurrence and extent of thin optical layers. These results were communicated to the other PIs by e-mail and used to guide ship-based sampling efforts. Analyses of these data during this next year will be used to (1) detect the presence, intensity, thickness, temporal persistence, and spatial coherence of thin optical and acoustical layers, (2) quantify their optical and acoustical characteristics, and (3) quantify their association with physical, chemical and biological structures and processes that have been hypothesized to control thin layer dynamics.

The second major component of our effort involved using the R.V. Shana Rae to periodically collect ship-deployed high-resolution profiles needed to (1) validate the measurements made by the autonomous optical profilers, (2) characterize the larger scale spatial variability in the fine-scale structure detected by the array, and (3) further characterize the inherent optical properties of thin layers detected by the array. Our high-resolution profiler had the same sensor suite as the bottom-up IOP profilers plus a PAR light sensor, a second WET Labs ac-9 with a 0.2 micron pre-filter for measuring spectral absorption by dissolved substances, a pair of WET Labs ac-s high-spectral resolution absorption and attenuation meters (one without and 1 with a 4 micron pre-filter to measure absorption, attenuation and scattering by small particles for spectral characterization of particulate and dissolved material), and a SubChem analyzer (provided by Hanson - see his report) for measuring fine-scale nutrient structure. We plan to combine these data with data from the array to define (1) the spatial variability along-shore and cross-shore in layer thickness, intensity, optical characteristics, and biological composition, and (2) the association of these changes with changes in the physical, chemical and biological structures and processes that have been hypothesized to control thin layer dynamics. We also plan to eventually combine these data with similar physical and optical data that Cowles collected in deeper water to determine the along-shore and cross-shore dimensions of any thin layers that extend outside the local region that we plan to sample.

The third component of our effort involved using the R.V. Shana Rae to periodically collect plankton samples from inside and outside thin layers. Real-time data from our high-resolution profiler was used to guide the collection of plankton samples from inside and outside thin optical layers using a rosette bottle sampler. Rines (see her LOCO report) is using these samples to identify the biological composition of the plankton. In addition, we collaborated with Holliday in using real-time data from his TAPS array to guide collection of net samples needed to identify the composition of zooplankton present and collect photographic images of zooplankton needed for inversion of the acoustic data on zooplankton distributions (as planned by Holliday). We also periodically towed our newly acquired Laser Optical Plankton Counter (LOPC) along the K line to collect optical data on the abundance, size and shape of the zooplankton that were being measured by Holliday's TAPS at K1 and K2 and by the multi-frequency acoustic profilers deployed from the Shana Rea by Benoit-Bird.

WORK COMPLETED

Reprocessing of ship-deployed high-resolution profiler data from LOCO 2005 and 2006. We have completed processing the physical and optical data collected during LOCO 2005 and 2006. We have corrected all the raw optical data for instrument drift, and the effects of temperature and salinity on the absorption of seawater. We have applied lags to compensate for time it takes water to flow from water intakes at the top of the profiler to individual sensors. We have used data from the 2 ac-9s (one with and a second without a 0.2 um pre-filter) to calculated multi-spectral absorption by particulate and dissolved materials using our standard dual ac-9 technique (Twardowski, et al, 1999; Sullivan et al, 2006). We have used an identical technique to calculated hyper-spectral absorption by particulate and dissolved materials using for the 2 ac-s instruments when they were configured one with and a second without a 0.2 um pre-filter. We have also fit a curve to the ac-9 multi-spectral dissolved absorption data and combined it with total absorption data from the ac-s to calculate hyper-spectral absorption by total particulate material. We have developed new software to calculate a multi-spectral and hyper-spectral derived optical products based on ratios and inversion models. The resulting data have been compiled into master data files.

Reprocessing of optical, physical and chemical data from ORCAS profilers deployed in LOCO 2005 and 2006. We have corrected all the raw optical data for instrument drift and the effects of temperature and salinity on the absorption of seawater. We have used the optical data from the high resolution profiler to check for drift of the sensors on the ORCAS profilers. We have applied lags to compensate for the time it takes water to flow from the intakes at the top of the profiler to individual sensors. We have removed the effects of surface wave induced pressure fluctuations by fitting a 7th order polynomial to the time-depth trace of each profile to yield the true depth as a function of time. Estimates of true depth were subtracted from measured depth to estimate variation in wave heights during each cast. These data were used to create master data sets for each profile. A time series master data set was created for each profiler location by concatenating the individual profiles into a large matrix table that could be plotted in Spyglass Transform.

ADV processing: The turbulent dissipation rate (ε), current magnitudes and fine-scale current shear were quantified using Nortek Vectors (64 Hz acoustic Doppler velocimeters) mounted on our ORCAS profilers. The Vector is a remote sensing three-dimensional velocity sensor with the resolution and response needed for both turbulence and fine-scale current measurements. To determine true horizontal current velocities, a multi-step processing technique was developed to remove both the effects of surface wave (and swell) induced pressure (depth) fluctuations and wave orbital velocities from the measured current velocities. Pressure fluctuations were removed by fitting a 7^{th} order polynomial to the time-depth trace of each profile to yield the true depth as a function of time. Per Nortek's recommendation, all velocity measurement points that had a <70% correlation factor were removed and replaced with NANs. After this step, all velocity outliers > 4 standard deviations of the average were removed. To remove the wave orbital velocities, we applied three consecutive running averages at box intervals of 45, 30 and 30 seconds (equivalent to using a triangular filter). This smoothed velocity data was then compared to a bottom mounted ADCP in the area (data courtesy of Mark Stacey, Margaret McManus and Jonah Steinbuck) and verified the Nortek Vector could yield robust estimates of the horizontal current structure.

The Vector estimates of fine-scale currents were subsequently used to calculate vertical shear gradients and Richardson numbers. *In situ* turbulent dissipation rate (ε) was estimated using the methods of Terray et al. (1996).

Evaluation of critical scales. Vertical shear gradients and shear related parameters (buoyancy frequency, Richardson number, etc.) were calculated over 3, 6, 10, 15, 20, 30, 50 and 100 cm integration intervals and analyzed for loss of structure or result artifacts. It was determined that we could reliable integrate over a 6 cm scale and yield good estimates

Published papers on earlier work and its implications. We have one paper in press this year and have a second in review. The first paper (Cheriton, et al, in press) examines the spatial patterns of formation of thin acoustic layers along the US west coast. The second paper (Churnside and Donaghay, in review) examines the frequency of occurrence, spatial extent, and characteristics of thin optical backscattering layers in coastal and open ocean areas of the North Pacific and North Atlantic using 80,000 kilometers of high vertical and horizontal resolution optical backscatter data collected by James Churnside (NOAA) during tests of an airborne LIDAR that he developed to survey epipelagic fish.

RESULTS

Temporal variation in physical, chemical and optical fine structure during LOCO 2006. The relative importance of physical forcing varied dramatically over the 2 weeks of the LOCO 2006 process study. Three distinct phases were evident when the physical, chemical and optical data were plotter as a time series (Figure 1, 2). During the first phase, upwelling favorable winds offshore combined with episodic local wind events induced a series of advection and mixing events that reduced phytoplankton biomass (Figure 1a), limited apparent oxygen production (Figure 1b and resulted in dramatic shifts in optical scattering (Figure 2b) and particle size distribution (Figure 2d). In contrast, during the second phase, low winds and clear sunny weather limited lateral advection and vertical mixing. The net result was a biologically dominated phase where high productivity resulted in multiple thin layers, high apparent oxygen production, (Figure 1b), increases in optical absorption, scatter and backscatter (Figures 2a,b,c), and the emergence of subsurface layers dominated by large particles (Figure 2d). At the beginning of the third phase, a pair of advection advents (Figure 1c) transported a new water mass into the location of the array. This water mass had lower optical absorption, scatter and backscatter (Figure 2a,b,c). During the third phase, physical forcing was more episodic and weaker than during the first phase. This allowed periodic development of thin layers (Figure 3) and an initial intensification of the sub-surface layer of large particles (Figure 2d). These results clearly indicate the power of the ORCAS profiler for not only providing the optical data needed to quantify the occurrence and characteristics of thin layers, but also for identifying the relative importance of physical and biological processes that control their dynamics.

Broad-scale patterns of occurrence of thin layers detected by LIDAR. Thin layers were observed in the airborne fish LIDAR data collected in a wide variety of ocean environments ranging from fjords and near shore waters to deep waters well off the shelf and far from the influences of coastal processes. For example, thin layers were seen in the deep waters of the Eastern Pacific off Oregon and Washington, the Gulf of Alaska and the Norwegian Sea, as well as the shelf waters off of Oregon, Washington, Alaska, Norway, and Portugal. Furthermore, thin layers were observed in a variety of physical environments ranging from the wind driven upwelling environments off of the west coasts Oregon, Washington, and Portugal, to regions where winds are normally unfavorable for upwelling such as the waters of the Gulf of Alaska. They were also found in regions with little freshwater inflow as well as regions with large local fresh water inflows. Finally, they were found down-stream of regions of topographic upwelling and in large eddies. These results clearly indicate the value of LIDAR for rapidly collecting the spatial data sets needed for addressing phenomenological questions about whether thin layers can occur in a region or under a set of forcing conditions.

Although thin layers occurred in most areas sampled, the frequency of occurrence, intensity and spatial extent of thin layers varied dramatically. For example, the frequency of occurrence ranged from highs of 20% in some areas (such as areas off Oregon and Washington during upwelling relaxation events) to frequencies of well below 1% in other areas (such as the Norwegian Sea and the Southern California Bight). Although some of these differences in are probably reflections of absolute regional difference in the ability of the system to support thin layers (or layers of any type as in the western Norwegian Sea), in other cases it almost certainly reflects the environmental conditions at the time of the LIDAR surveys. For example, the differences seen between the waters off of the US Pacific Northwest and the California Bight are almost certainly a reflection of the fact that intense local winds off California were suppressing thin layers at the time of the survey, while the upwelling relaxation conditions off the Pacific Northwest were favorable for thin layer development during that study. This is even more evident in those cases where thin layers detected before storms were not detected in subsequent flights during or after the storm. These results are consistent with models of the thin layer mechanisms [Donaghay and Osborn, 1997] and with our observations in Monterey Bay during LOCO.

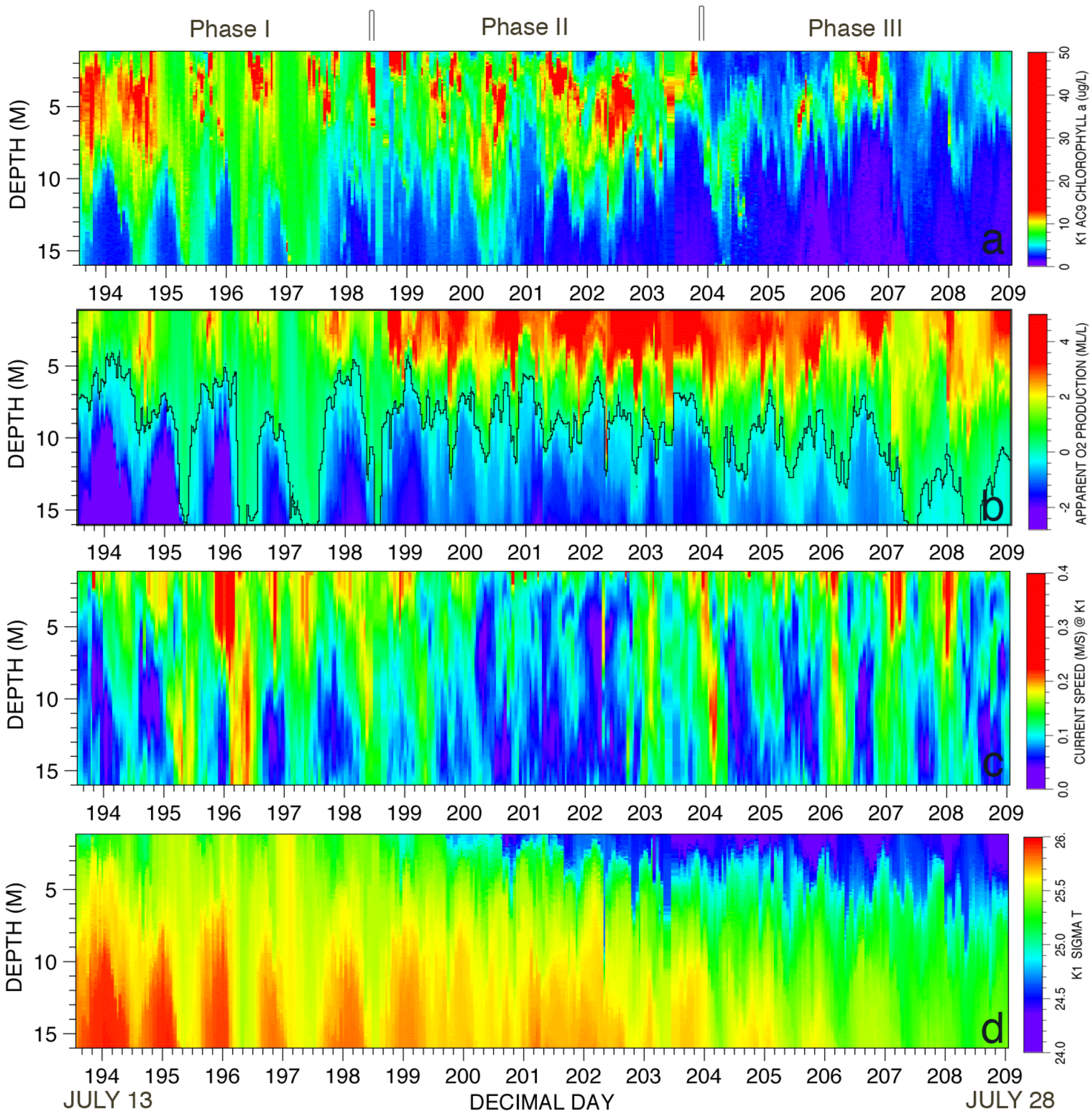

Figure 1. Temporal variation during LOCO 2006 in chlorophyll a (1a), apparent oxygen production (1b), current speed (1c) and density (sigma t) (1d) at K1 as measured hourly at centimeter scales by the autonomous ORCAS profiler. The figure illustrates the three phases of biological response: during Phase I, physical forcing dispersed an initial algal bloom (1a) and suppressed primary production (1b); during Phase II, reduced winds lead to reduced current speeds (1c), increased stratification (1d), increased apparent phytoplankton production (1b), and the development of multiple thin layers of algae (1a); and during Phase III, clear skies allowed further increased stratification (1d) and high apparent oxygen production (1b) despite lower phytoplankton biomass (1a) and episodic wind driven currents that advected water masses with their associated phytoplankton (1a) and apparent oxygen production (1b) through K1.

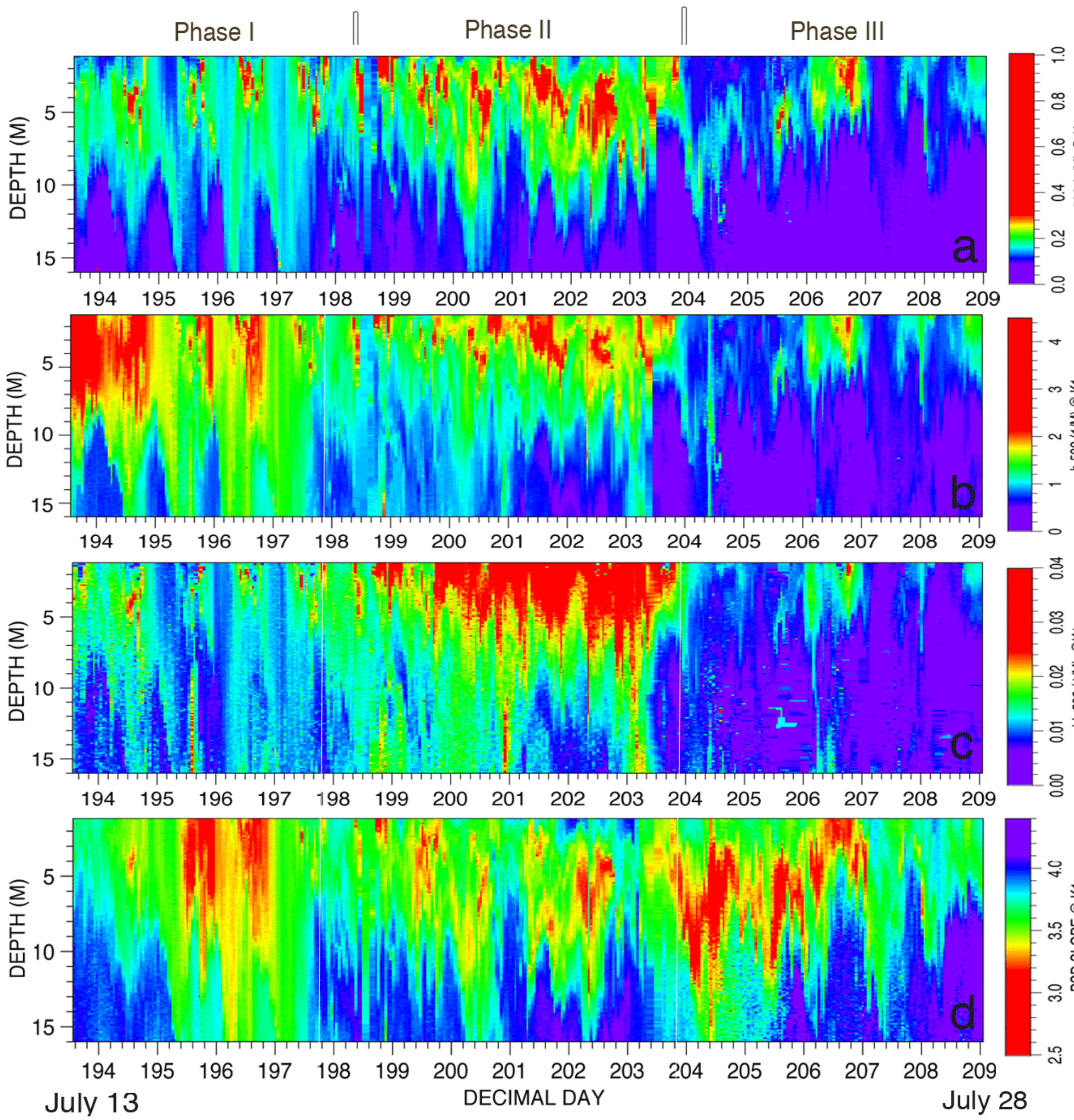

Figure 2. Temporal variation during LOCO 2006 in the fine-scale vertical structure of absorption at 532 nm (2a), scattering at 532 nm (2b), backscattering at 532 nm (2c), and particle size distribution slope (2d) as measured hourly at centimeter scales by the autonomous ORCAS profiler at station K1 in northeastern Monterey Bay. The figure shows that while the absorption, scattering and backscatter were elevated during the Phase II and reduced during Phase III, absorption and back scattering were uncorrelated with scattering in Phase 1. The figure also shows that there were major temporal shifts in particle characteristics as evidenced by changes in scattering relative to absorption and back scattering during the first 2 days of Phase 1 and the decrease in PSD Slope (2d) in Phase III that was uncorrelated with changes in absorption, scattering or backscattering.

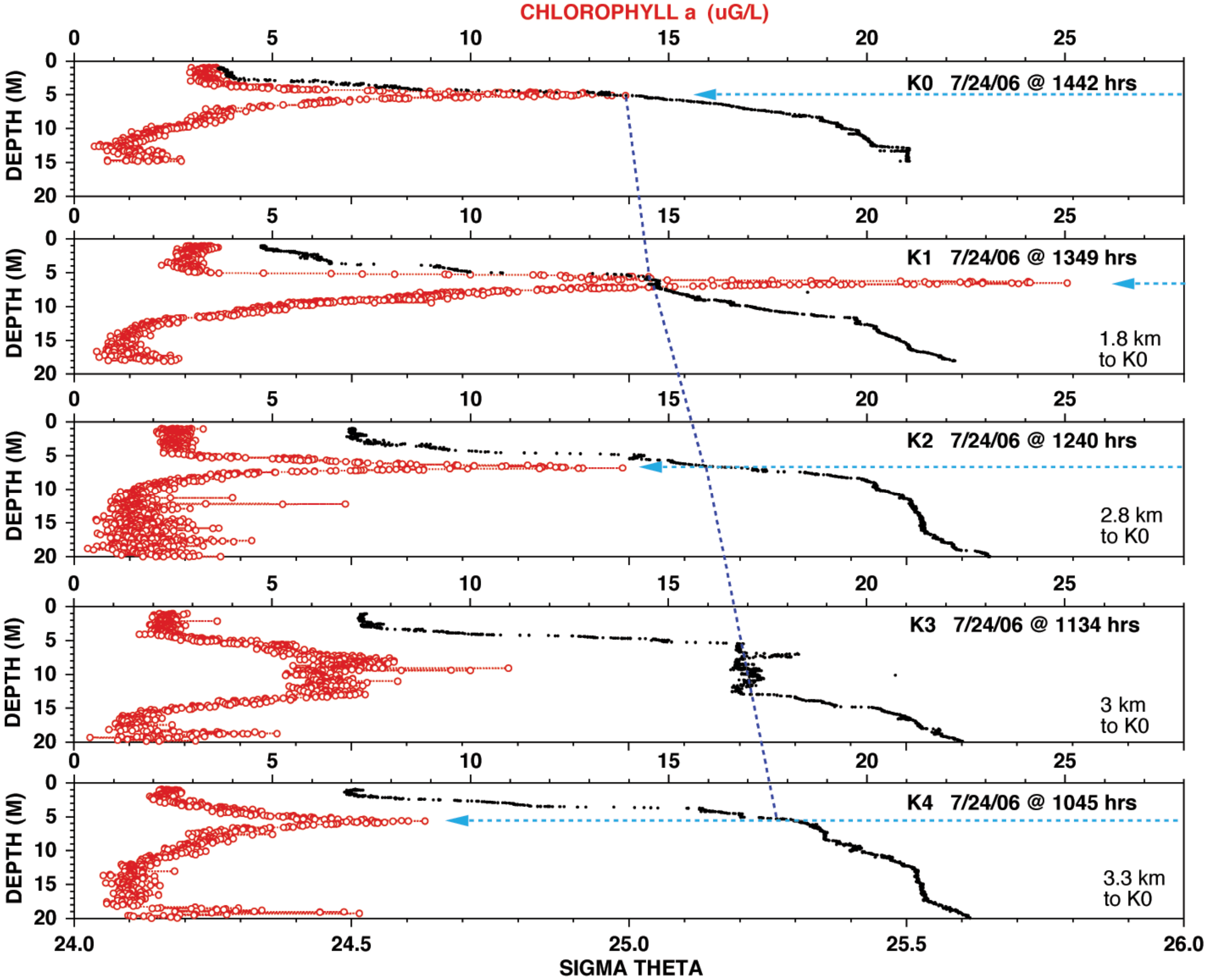

Figure 3. Spatial coherence of fine-scale vertical structure of chlorophyll a [estimated from the ac-9 data] (circles) and density (black dots) along the 3.8 km long cross-shelf K line in northeastern Monterey Bay, CA. The K line extends from 15 m deep water at K0 at 36° 56.61' N and 121° 54.71' W to 21.9 deep water at K4 at 36° 55.63' N and 121° 55.70' W. The dashed arrows (cyan) indicate the depth of thin layers and the diagonal dashed line (blue) indicates the progressive deepening of the density at which the layer was observed. These data were collected with our ship-deployed Hi-Res profiler on July 24 during the 2006 LOCO experiment. The figure shows that while a thin layer was observed at K0, K1, K2 and K4, only a broad chlorophyll a maximum was observed at K3. This thin layer was spatially coherent over at least 2.8 km. The figure also shows that while the thin layers at K0, K1, K2 and K4 were associated with regions of steep density gradient and progressively higher density waters, the broad chlorophyll a maxima at K3 was associated with an unstable density gradient similar to that observed after an internal wave breaks.

Broad-scale patterns of spatial coherence of thin layers detected by LIDAR. Three distinctly different patterns of spatial coherence were evident in the LIDAR data. Each of these types of layers will be discussed in sequence below. *Class 1:* These thin layers were self-contained features that were consistently less than 3-4 m thick and showed spatial coherence over scales of kilometers. For example, a thin layer seen off of Portugal (Figure 4) was spatially coherent over 10 kilometers while one seen in the Gulf of Alaska south of Kodiak Island was spatially coherent over nearly 2 kilometers. These thin layers are of similar length to the 2.8 km long thin layer seen in our Monterey Bay transect (Figure 3). This class of layers frequently varied in depth in response to internal waves, but had no thickened regions and no regions where the layer became too thin or too weak to be detected by the LIDAR. Such spatially coherent structures are consistent with the idea that episodic shear events can spread plankton patches into thin layers that remain spatially coherent over scales of multiple kilometers [Donaghay and Osborn, 1997]. Such layers can also be generated behaviorally when plankton aggregate along a spatially coherent feature such as a nutricline as we saw during LOCO 2005. The spatial coherence (lack of gaps) of such thin layers suggests that localized vertical mixing events (from shear instabilities and breaking internal waves) have not occurred over the length scale of the thin layer during its recent development. *Class 2:* These thin layers were clearly parts of much longer layers that had both regions that qualified as thin layers and regions where the layer became more intense and much thicker than the 3 m criteria. This pattern is consistent with what we might expect to see if episodic increases in current shear spread a series of plankton patches into thin layers [Donaghay and Osborn, 1997]. In some cases these thin layers were thin segments of layers that extended for hundreds of kilometers. *Class 3:* These thin layers appeared to be part of a larger scale structure that was broken into shorter segments by gaps where either (1) the layer became too thin or too weak to be detected by the LIDAR (as might be expected if we were crossing a set of filaments), or (2) the layer became much less intense but thicker (as might be expect if a thin layer were disrupted by a localized mixing event similar to that seen in our Monterey Bay transect (Figure 4c).

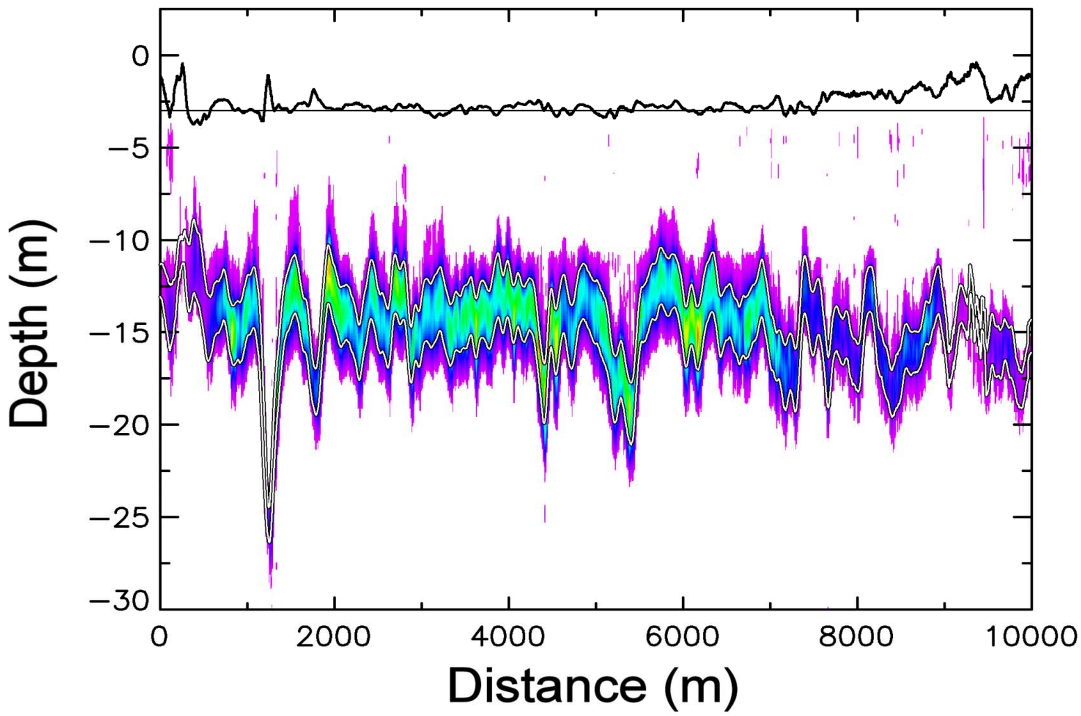

Figure 4. Spatial coherence of a 10 km long thin optical layer off the coast of Portugal detected by the NOAA airborne fish LIDAR. The LIDAR transect extended from 8.9506 W, 41.1847 N to 8.9185 W, 41.1010 N in 66 m deep water. The white lines denote the half power points above and below the peak, the thick black line at the top is the negative of the layer thickness, and the thin line is -3 m. The figure shows a spatially coherent, 10 kilometer long thin layer that varies in depth between 12 and 25 m, but shows no gaps or regions where it thickens beyond 3.6 m. This figure is from Churnside and Donaghay (submitted JGR).

IMPACT/APPLICATION

One of the central assumptions in biological oceanography has been that small scale mixing processes in the upper ocean are sufficiently strong and equal in all directions that sub-meter scale biological, chemical and optical structures will be rapidly dispersed and thus can be ignored in both sampling and modeling upper ocean dynamics. Results from our measurements of finescale structure in East Sound (WA), Monterey Bay (CA), the Gulf of Mexico, and off the west coast of Ireland clearly indicate that this assumption is frequently incorrect. These measurements also indicate that the accurate assessment of occurrence, intensity, spatial extent, and temporal persistence of thin optical layers requires centimeter-scale sampling. Our field results and theoretical analyses indicate that biological-physical, biological-chemical and biological-biological interactions occurring at these scales may control not only the development of blooms of toxic and/or bioluminescent phytoplankton, but also the extent to which zooplankton are able to exploit phytoplankton production. Equally importantly, collaborative analysis of the data with experts in optics indicates that fine-scale biological layers can become sufficiently intense at times to alter the performance of optical and acoustical sensors in coastal waters.

These analyses also suggest that our bottom-up profiling systems have considerable potential for increasing our understanding biological dynamics and improving our interpretation of optical and acoustic data collected by other platforms.

TRANSITIONS

Our ORCAS profiler technology has now been successfully transitioned to four different groups through our collaborative efforts to commercialize the technology with WET Labs. First, Dr. Benjamin Cray (NUWC) has purchased and successfully deployed a modified Mini-AMP version of the profiler equipped with a CTD, ADV and an array of advanced acoustic sensors. Second, Jim Sullivan has worked with WET Labs in deploying an advanced optics version of the mini-AMP profiler during ONR's OASIS experiment off Martha's Vinyard in September 2007. Third, we have collaborated with WET Labs and Jack Barth (OSU) in developing an NSF funded version of the profiler suitable for extended deployment on the Oregon shelf. Fourth, NOAA has purchased and successfully deployed a WET Labs Mini-AMP profiler for use in one of its programs in Chesapeake Bay.

We have also continued out efforts to transition the optical calibration and data processing techniques we have developed for the WET Labs ac-9 and ac-s (Sullivan, et al, 2006). During this past year, we have continued to work with WET Labs to transition the data processing techniques into their software. In addition, Jim Sullivan gave a short course on calibration and field application of these instruments during the 2007 ocean optics meeting.

RELATED PROJECTS

This LOCO project has been developed in close collaboration with Van Holliday (URI/BAE Systems) and a core group of independent investigators that include Jan Rines (URI), Louis Goodman (SMAST), Edward Levine (NUWC), Alfred Hanson (SubChem Systems), Margaret McManus (UH), and Timothy Cowles (OSU). We have collaborated with these investigators for several years. This year we have worked closely with Goodman in the analysis of the ADV and other physical data collected during the LOCO experiments. We have shared data sets with Goodman and Sullivan has worked closely with him in designing our approach to analyzing the turbulence data from the ADV. We have also work closely with Hanson in analyzing the nutrient data collected by our autonomous ORCAS IOPC profiler and ship-deployed Hi-Res profiler.

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